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THE DESIGN OF A RANGE FINDER FOR A COMPUTER VISION SYSTEM

RODERICK JAMES FLETCHER

UNIVERSITY OF ILLINOIS – URBANA, ILLINOIS

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A computer vision system has been developed at the Coordinated Science Laboratory (CSL) which enables a PDP-10 computer to acquire television pictures in digital form. The television camera is mounted on a platform referred to as the pan-tilt assembly which can be rotated back and forth and tilted up and down. Also on the pan-tilt assembly are a remote controlled zoom lens and a range finder. Everything on the pan-tilt assembly except for the camera is interfaces to a PDP-11/40 minicomputer which can communicate with the PDP-10.

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THE DESIGN OF A RANGE FINDER FOR A COMPUTER VISION SYSTEM

by

Roderick James Fletcher

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THE DESIGN OF A RANGE FINDER FOR A COMPUTER VISION SYSTEM

BY

RODERICK JAMES FLETCHER

B.S.E.E., Bradley University, 1974

THESIS

Submitted in partial fulfillment of the requirements
for the degree of Master of Science in Electrical Engineering
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Thesis Advisor: Professor Robert T. Chien

Urbana, Illinois

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Special thanks also goes to Bob Fults and Robert Bales for machining nearly all of the mechanical parts of the range finder, and to Cliff Geschke, Charles Jacobus, and Don Williamson for thoughtful suggestions regarding the range finder electronics and for facilitating the interfacing of the range finder to the PDP-11 through the use of general register cards (designated herein as the position registers and the control and status register) and the interrupt card which they had designed.

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I. INTRODUCTION

A computer vision system has been developed at the Coordinated Science Laboratory (CSL) which enables a PDP-1Ø computer to acquire television pictures in digital form. The television camera is mounted on a platform referred to as the pan-tilt assembly (see Fig. 1) which can be rotated back and forth and tilted up and down [Geschke, 1975]. Also on the pan-tilt assembly are a remote controlled zoom lens [Williamson, 1975] and a range finder. Everything on the pan-tilt assembly except for the camera is interfaced to a PDP-11/4Ø minicomputer which can communicate with the PDP-1Ø.

The device that was most recently added to the vision system is the range finder. By projecting a stripe of light onto the scene being viewed by the camera, distances to the points illuminated by the stripe can be computed by triangulation. The source of light is a 15 milliwatt helium-neon laser, and the laser beam is converted into a stripe and projected by a specially built scanning head. This part of the range finder is patterned after a similar range finder used at Stanford [Agin and Binford, 1973]; however, the CSL version is mounted differently. Instead of being attached to a table, the laser and scanning head are mounted on the pan-tilt assembly with the camera so that the range finding facility is always available no matter where the camera is aimed. Furthermore, this arrangement reduces the need for frequent readjustment of the range finder since the relative position of the laser and scanning head is fixed.

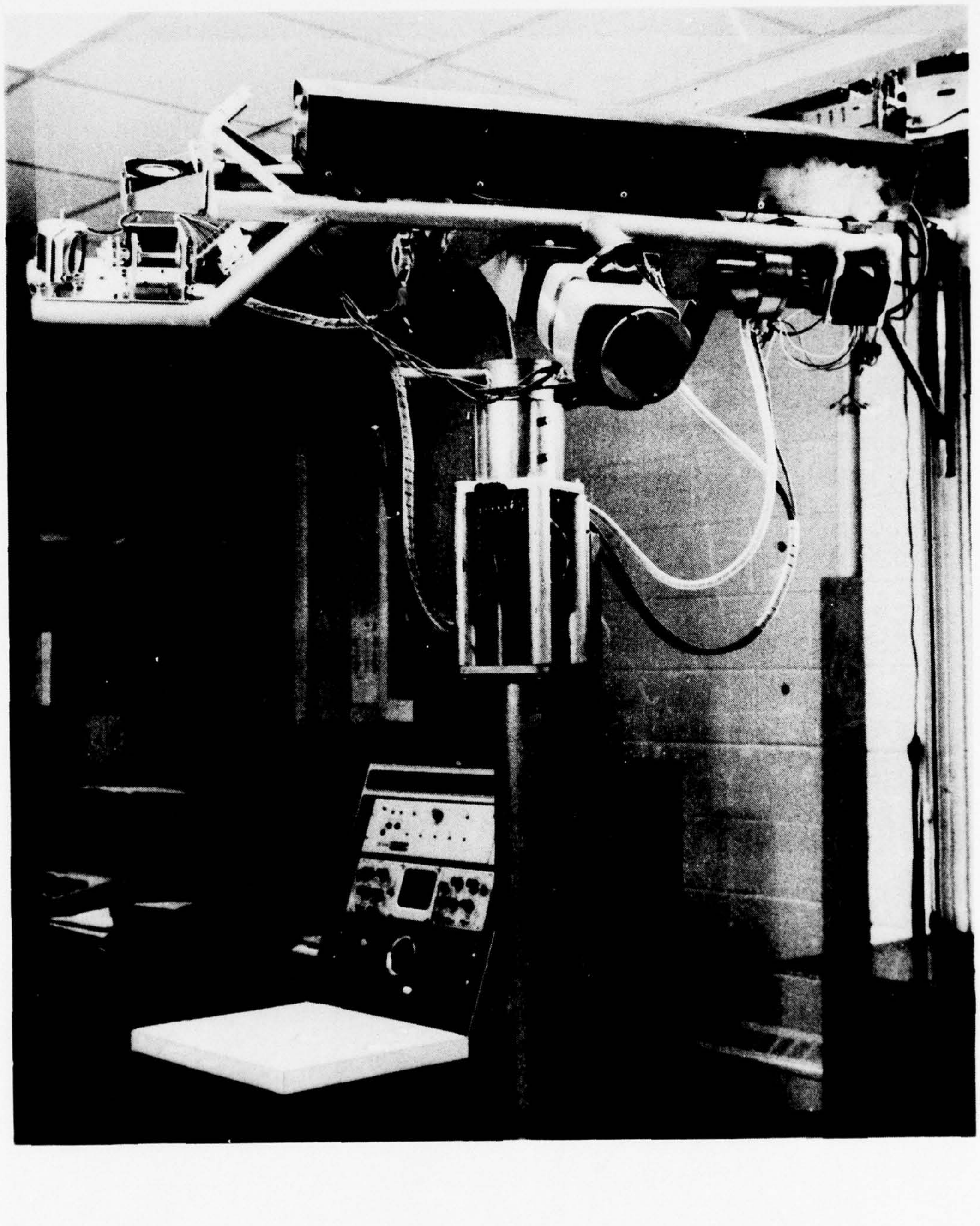

Fig. 1. The pan-tilt assembly.

The scanning head consists of two main parts, a lens rotating assembly and a mirror assembly mounted on a common chassis. A schematic view of the scanning head is shown in Fig. 2. The laser beam encounters the lens assembly first. In the shape of a semicircular cylinder, the lens causes the laser beam to spread out in only one dimension. This creates a plane of light , or a stripe as seen by the camera. The orientation of the plane is controlled by the rotation of the lens about the axis of the laser beam. Before the plane of light becomes too wide, it is reflected by a small mirror towards the area being viewed by the camera. Hence, the distance to virtually any point in the camera's image can be obtained.

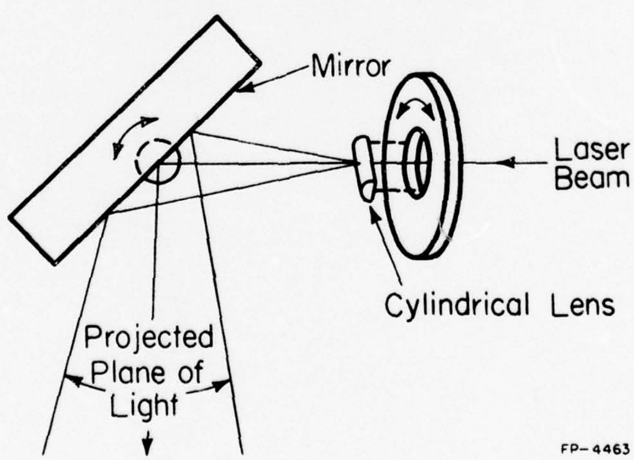

Fig. 2. Schematic of the scanning head.

Of course, in order to accurately measure distances, the orientation and scanning angle of the plane of light must be known very precisely. Consequently, the lens and mirror are driven by stepper motors which are controlled by the PDP-11. The motors are geared down so that the lens moves in angular increments of five degrees and the mirror in increments of 0.05 degrees. (Note, however, that the net increment in the scanning angle is one tenth of a degree.)

Control of the scanning head by the PDP-11 is simplified by some logic circuitry at the interface. Both the lens and the mirror have a pair of position registers, one for the actual position and one for the desired position. The computer need only load the desired positions and the hardware controls the motors automatically. When the motors, i.e., the lens and mirror, have reached their desired positions, the hardware can signal an interrupt to the computer.

II. PRINCIPLES OF OPERATION

The basic method used to determine the range of an object is triangulation. The scanning head projects a plane of laser light which can be seen as a stripe in the camera's image, while each point in the image corresponds to a ray in space along which the observed point must actually lie. This ray intersects the plane in a unique point. If the equations of the ray and the plane are known in a suitable coordinate system, then the coordinates of the intersection point can be computed.

Since the camera and the scanning head are both rigidly affixed to the pan-tilt platform, it is convenient to use a coordinate system also attached to this platform. Such a system is shown in Fig. 3. In order to simplify the subsequent analysis, the following assumptions will be made. (1) The axis about which the scanning mirror rotates shall be parallel to the z axis, and the surface of the mirror shall contain this axis of rotation. (2) The axis of the laser beam shall lie in the x-y plane and intersect the mirror's axis of rotation. (3) The cylindrical lens shall be adjusted so that the plane of light rotates about the axis of the laser beam.

When the above assumptions are satisfied, the orientation and scanning angle of the projected plane of light can be measured by the angles Θ and Φ as shown in Fig. 4. Both angles are shown with a positive displacement. Hence, the direction angles of the plane are given by

$$\cos \alpha = \frac{b \cos \Theta \cos \Phi}{b} = \cos \Theta \cos \Phi$$

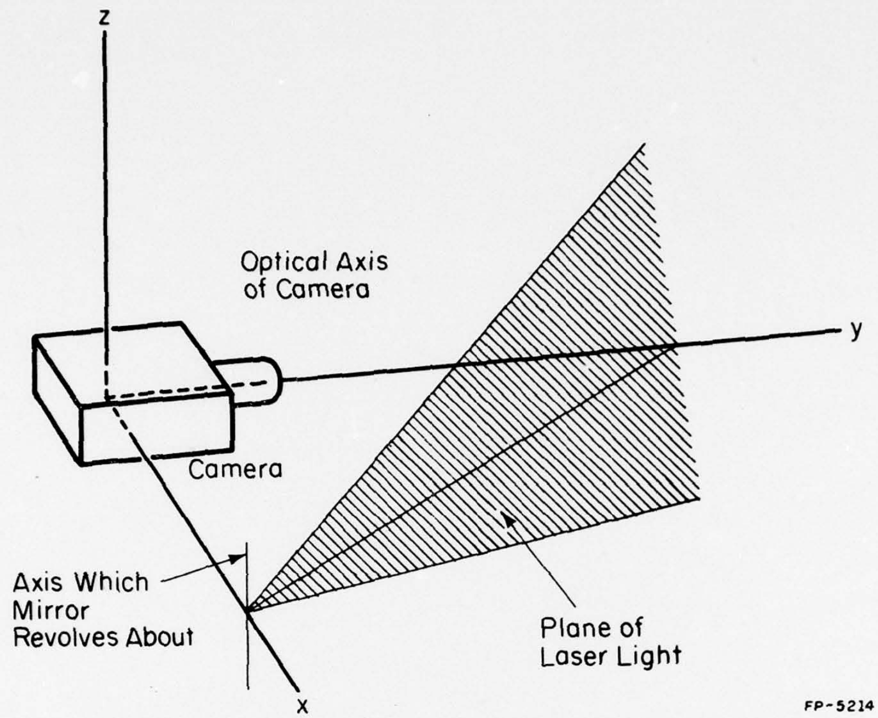

Fig. 3. The range finder coordinate system.

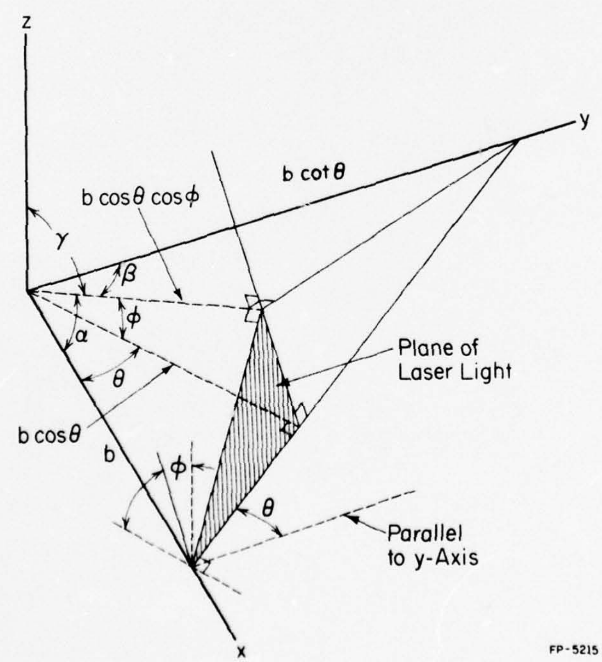

Fig. 4. Diagram of the projected plane of light.

$$\cos \beta = \frac{b \cos \Theta \cos \Phi}{b \cot \Theta} = \sin \Theta \cos \Phi$$

$$\cos \gamma = \cos(90^{\circ} - \Phi) = \sin \Phi,$$

and since the distance from this plane to the origin is $b \cos \Theta \cos \Phi$, the equation of the plane is given by

$$x \cos \Theta \cos \Phi + y \sin \Theta \cos \Phi + z \sin \Phi - b \cos \Theta \cos \Phi = 0. \qquad (1)$$

Since a ray extended from any point in the camera's image passes through an imaginary focal point located at $(0,f,0)$ on the y axis, it is convenient to express these rays in terms of a primed coordinate system centered at this point as shown in Fig. 5. Hence, we must first express the above plane in terms of the primed coordinates. From analytic geometry, the distance from the point $(0,f,0)$ to the plane in the unprimed coordinate system is given by letting $x = 0$, $y = f$, and $z = 0$ in the left side of Eq. (1). Since this distance simplifies to $(f \sin \Theta - b \cos \Theta)\cos \Phi$ and since the direction angles are unchanged in the primed coordinate system, the new equation for the plane of light is given by

$$x' \cos \Theta \cos \Phi + y' \sin \Theta \cos \Phi + z' \sin \Phi$$
$$+ (f \sin \Theta - b \cos \Theta)\cos \Phi = 0. \qquad (2)$$

The points in the camera's image can be imagined to lie on a front image plane with its points designated by the coordinates u and v. However, the location of this image plane is ambiguous; if it is close to the focal point, a small image is obtained, and if it is far away, a large image is obtained. To get around this problem, we can access points in the image plane by angular displacements from the y axis; hence, we define μ and ν as follows:

$$\tan \mu = \frac{u}{p-f}, \qquad \tan \nu = \frac{v}{p-f}.$$

A point (μ,ν) in the image, then, corresponds to a line in space given by the parametric equation (in the parameter y')

$$x' = y'\tan\mu, \qquad z' = y'\tan\nu. \tag{3}$$

The intersection of this line and the plane defined above can be found by substituting x' and z' from Eq. (3) into Eq. (2). Hence, we have

$$y'\tan\mu\cos\Theta\cos\Phi + y'\sin\Theta\cos\Phi + z'\tan\nu\sin\Phi$$
$$+ (f\sin\Theta - b\cos\Theta)\cos\Phi = 0,$$

or

$$y' = \frac{b\cos\Theta - f\sin\Theta}{\tan\mu\cos\Theta + \sin\Theta + \tan\nu\tan\Phi}.$$

The x' and z' coordinates can be easily found from Eq. (3). In the unprimed coordinates, the values are the same except that $y = y' + f$.

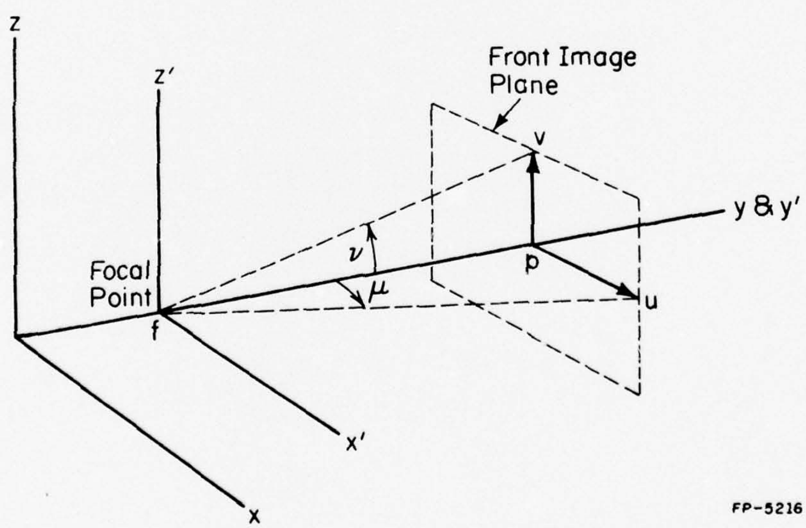

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Fig. 5. The image coordinate system.

III. THE SCANNING HEAD

The function of the scanning head is to convert the laser beam into a stripe and to aim the stripe toward the area being viewed by the camera. As shown above in Fig. 2, this is achieved with a cylindrical lens and a scanning mirror. The actual scanning head is shown in Fig. 6. The laser beam enters on the right through a hollow shaft on the lens rotating assembly (the unit assembled on the U-shaped bracket). At the end of this shaft is the lens mounting assembly with the cylindrical lens located at the very tip. Then at the left is the scanning mirror, and the motors which drive the mirror and lens are in the background.

From a design point of view, accomodating the assumptions made in the above mathematical treatment was a trivial problem. The following constraints were imposed upon the design: the axis of the hollow shaft was to intersect and be perpendicular to the scanning mirror's axis of rotation; the flat side of the cylindrical lens was to be perpendicular and centered with respect to the incident laser beam; and the surface of the scanning mirror was to contain the axis about which it rotates. In order to satisfy these constraints to the necessary degree of precision, the assemblies were designed to be adjustable wherever possible. Detailed views of these assemblies are given in Appendix A, and the procedure for making the adjustments is given in Appendix B.

In addition to those constraints which simplified the mathematical analysis, there were other design considerations. One very small detail was the way the laser beam should pass through the cylindrical lens to produce as

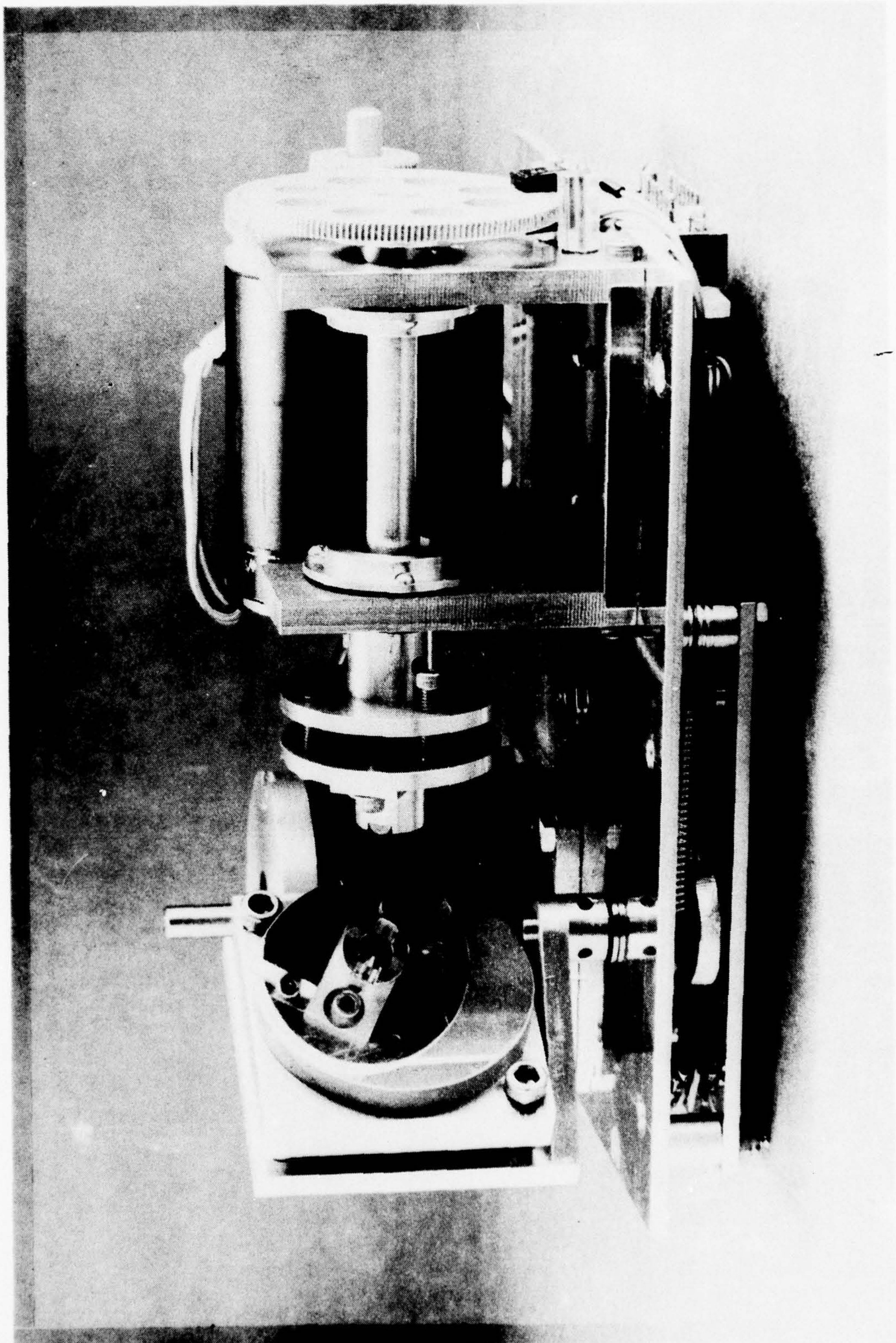


Fig. 6. Photograph of the scanning head.

long a stripe as possible; should it enter the flat side or the round side? The path followed by a ray of light in each case is depicted in Fig. 7. Using Snell's law from optics and letting n be the index of refraction for the cylindrical lens, we have

$$\sin \theta_f = \sin \theta_i \ (n\sqrt{1 - \sin^2\theta_i} - \sqrt{1 - n^2\sin^2\theta_i})$$

and

$$\sin \theta_r = \sin \theta_i \ (\sqrt{n^2 - \sin^2\theta_i} - \sqrt{1 - \sin^2\theta_i}).$$

These deflection angles for light entering the flat and round sides respectively are plotted versus $\sin \theta_i$ in Fig. 8. (The reason $\sin \theta_i$ is used as the independent variable instead of θ_i is that it is proportional to the distance by which an incident ray of light is off from the center of the lens.) Since the width of the laser beam is quite a bit less than the width of the lens, it can be seen that slightly greater angles of deflection are obtained for light entering the flat side.

As the light rays emerging from the cylindrical lens diverge, it is conceivable that some of these rays might completely miss the scanning mirror. Clearly, this problem is most prevalent when the mirror is turned as illustrated in Fig. 9a. Similarly, when the mirror is turned so that it is more nearly facing the lens as shown in Fig. 9b, the lens and its mounting assembly may intercept some of the light reflected by the mirror thus casting a shadow. In either case, there is a possiblity that blind spots may be produced in the range finder. Hence, an additional design consideration was to minimize these effects and to make sure that the entire field of view for the camera could be illuminated by the range finder. (It should be pointed out that blind spots can be produced by yet a third phenomenon over which there is no control. Since the scanning head must be displaced from the

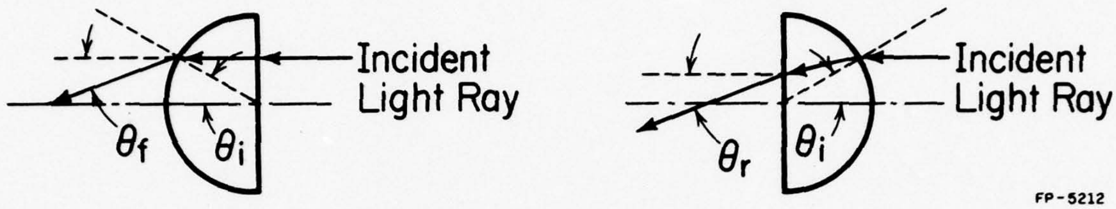


Fig. 7. The paths taken by a ray of light through the cylindrical lens when light enters the flat side (left) and the round side (right).

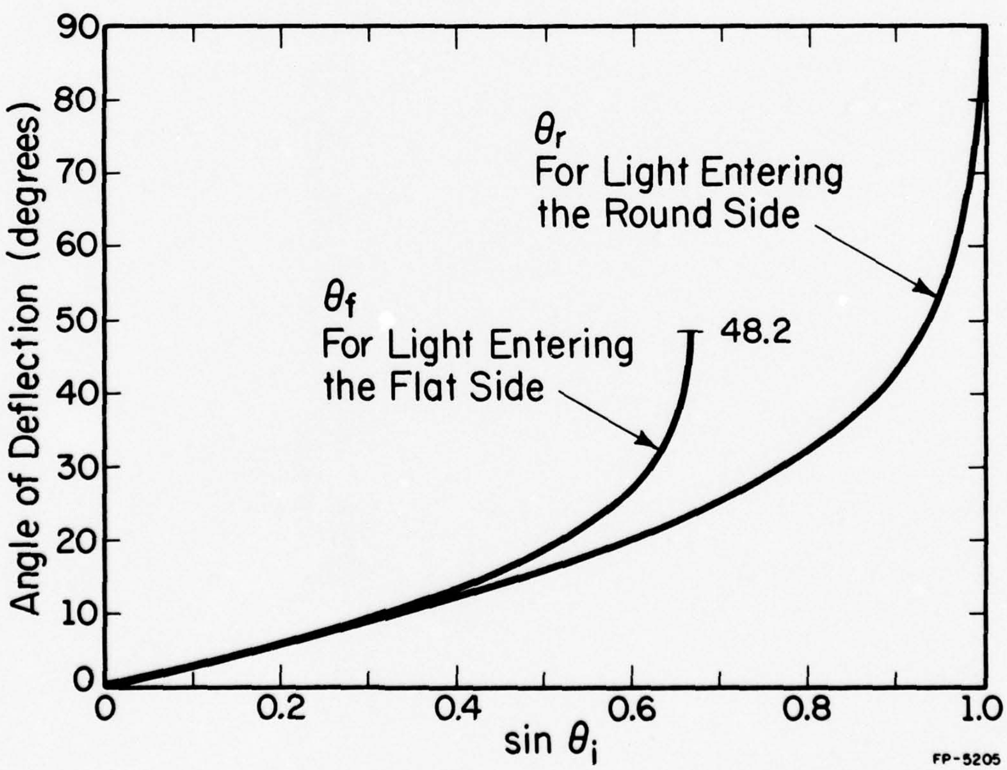
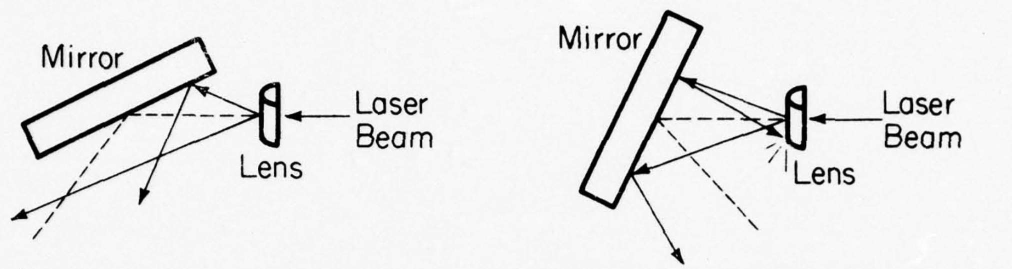


Fig. 8. Deflection angles plotted versus sin Θ_i where the index of refraction (n) is assumed to be 1.5.

optical axis of the camera, the projected stripe can fall on surfaces which cannot be seen from where the camera is located.)



(a) Light Missing the Mirror (b) Light Intercepted by the Lens

Fig. 9. Effects producing blind spots in the range finder.

Several factors were considered which might alleviate the problem of blind spots. One was the distance of the lens mounting assembly from the mirror. When the lens is moved closer to the mirror, less light misses the mirror, but at the same time, the problem of shadows becomes worse. Two other factors considered were the dimensions of the lens mounting assembly and the possiblily of mounting the whole scanning head at an angle slightly facing the optical axis of the camera. By far the most promising consideration, however, was the idea of mounting the scanning mirror so that it would rotate about a line offset from the center of the mirror as shown in Fig. 10. Not only does this result in the side of the mirror farther from the lens to subtend an angle from the lens more nearly equal to the angle subtended by the near side, but it also allows the lens to be moved closer to the mirror without danger of the mirror colliding with the lens when it turns fully clockwise.

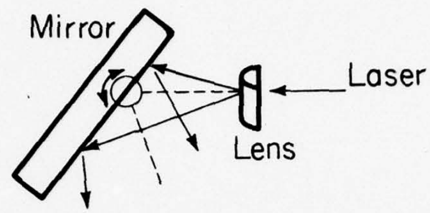


Fig. 10. Rotating the mirror about a line offset from the center of the mirror.

Of these considerations, only the first could be adjusted after the construction and mounting of the scanning head (since the lens mounting assembly can be slid back and forth on the hollow shaft). The other considerations, however, had a direct effect on the design of the scanning head. Hence, some method for determining when the design minimized the occurrence of blind spots had to be devised. An attempt was made to solve the problem analytically, but the analysis became too difficult. Consequently, a computer program was written to simulate a model of the scanning head. Given the parameters described above and the orientation of the cylindrical lens, the program would scan the stripe across the entire field of view in increments of ten degrees. The output of the program was the set of endpoints of all stripes and shadows cast upon a rectangular sheet of specified size and distance from the camera. Fig. 11 shows a typical output of the program illustrated graphically. By trial and error, it was found that the use of mirror offset alone was sufficient to shift all blind spots to well outside the camera's normal field of view.

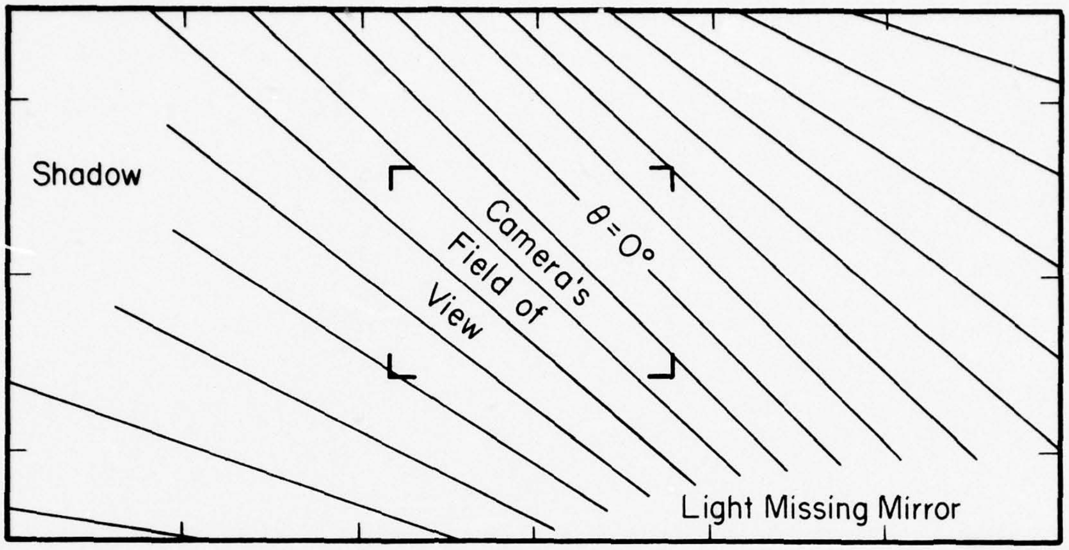


Fig. 11. Simulated scan of the range finder across a rectangular sheet (rectangular sheet: 3 m. by 6 m. in size, 2 m. from camera; baseline = 70 cm.; mirror offset = 1 cm.; Φ = 45 degrees).

We turn now to the means by which the mirror and lens are rotated. As pointed out above, the positions of the mirror and lens must be known with fairly high accuracy, so it was decided to drive them with stepper motors. Since fine adjustment of the lens rotation was not deemed critical, a motor with 24 steps per revolution and a single pair of gears with a 3:1 turning ratio was chosen to drive the lens. This provides a rotation in increments of five degrees, and it allows orthogonal stripes to be produced, e.g., at -45 and +45 degrees. Fine adjustment of the mirror's position, on the other hand, was considered more critical or else small objects in the camera's image might get skipped by the stripe as it scans back and forth. In other words, it was desired that the stripe move in increments not much larger than the width of the stripe. Hence, a motor with 200 steps per revolution was selected, and in order to reduce the increments in the scanning angle down to the required amount, i.e., one tenth of a degree, a gear reduction of 36 was required. The arrangement of the motors and gears is shown in Appendix A.

IV. THE RANGE FINDER ELECTRONICS

The electronic hardware which controls the range finder is distributed in three locations, but most of it is concentrated in the PDP-11 backplane. A block diagram of how it is distributed and the main paths of information flow are illustrated in Fig. 12. Although it is not shown, every block except for the control and status block consists of two virtually identical halves corresponding to the mirror and lens.

Since the motor controllers play such a central role, they should be described first. The schematic for a controller is shown in two parts in Figs. 13 and 14. In essence, the controller has two inputs and two outputs. One input is to drive the motor clockwise by producing a train of pulses on the clockwise output, and the other input and output drive the motor counter-

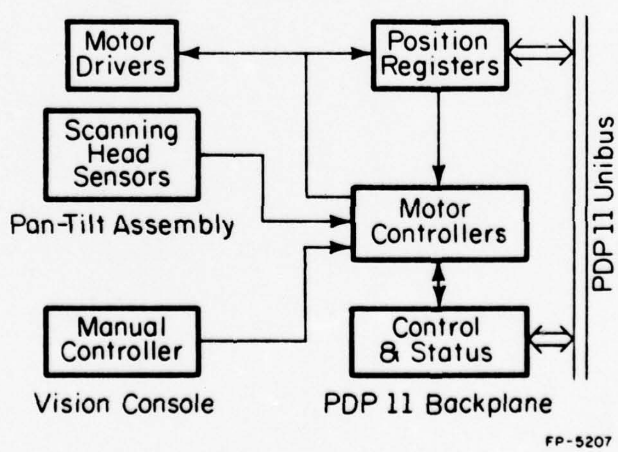


Fig. 12. Block diagram of the range finder electronics.

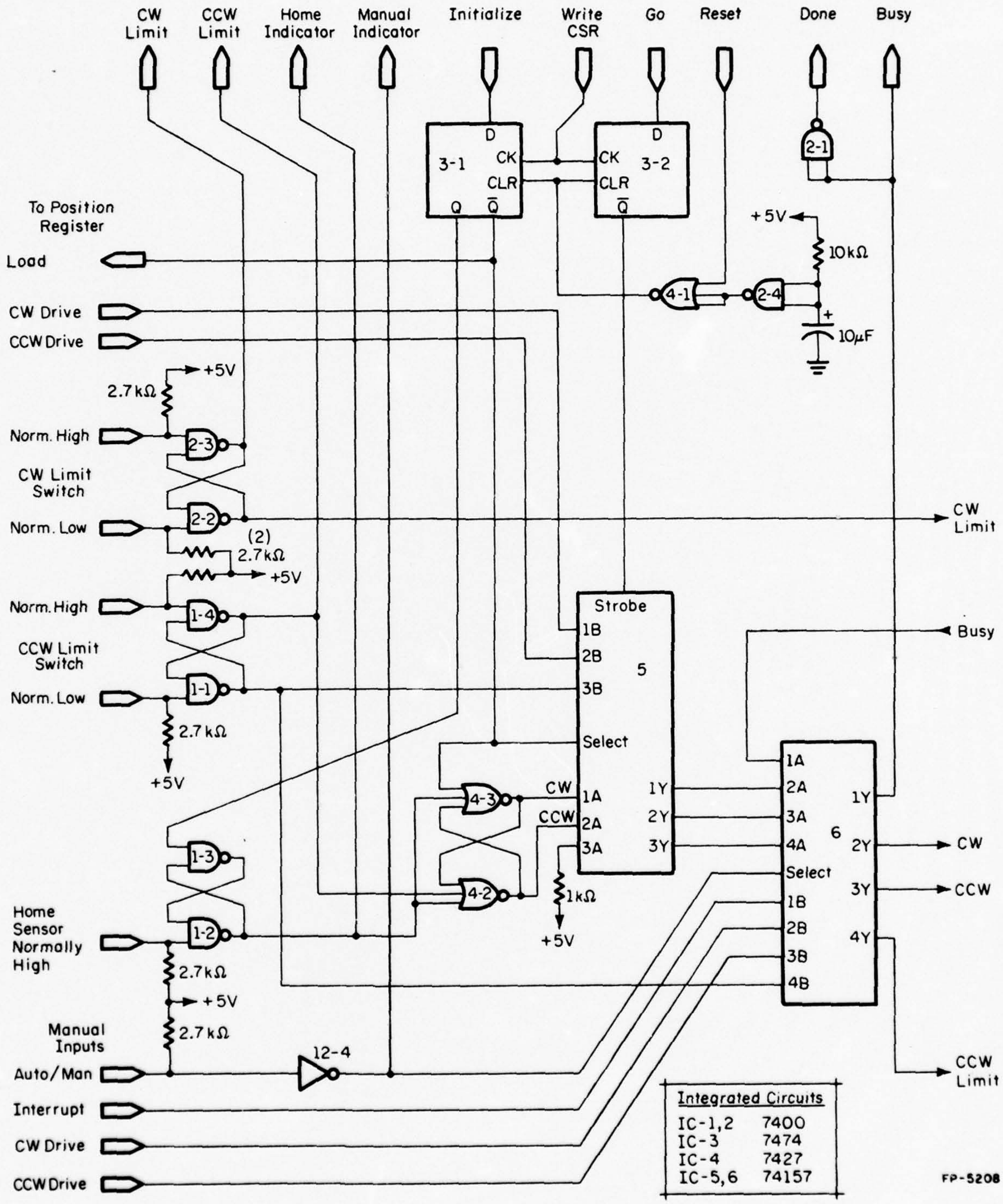


Fig. 13. Input circuitry of the motor controller.

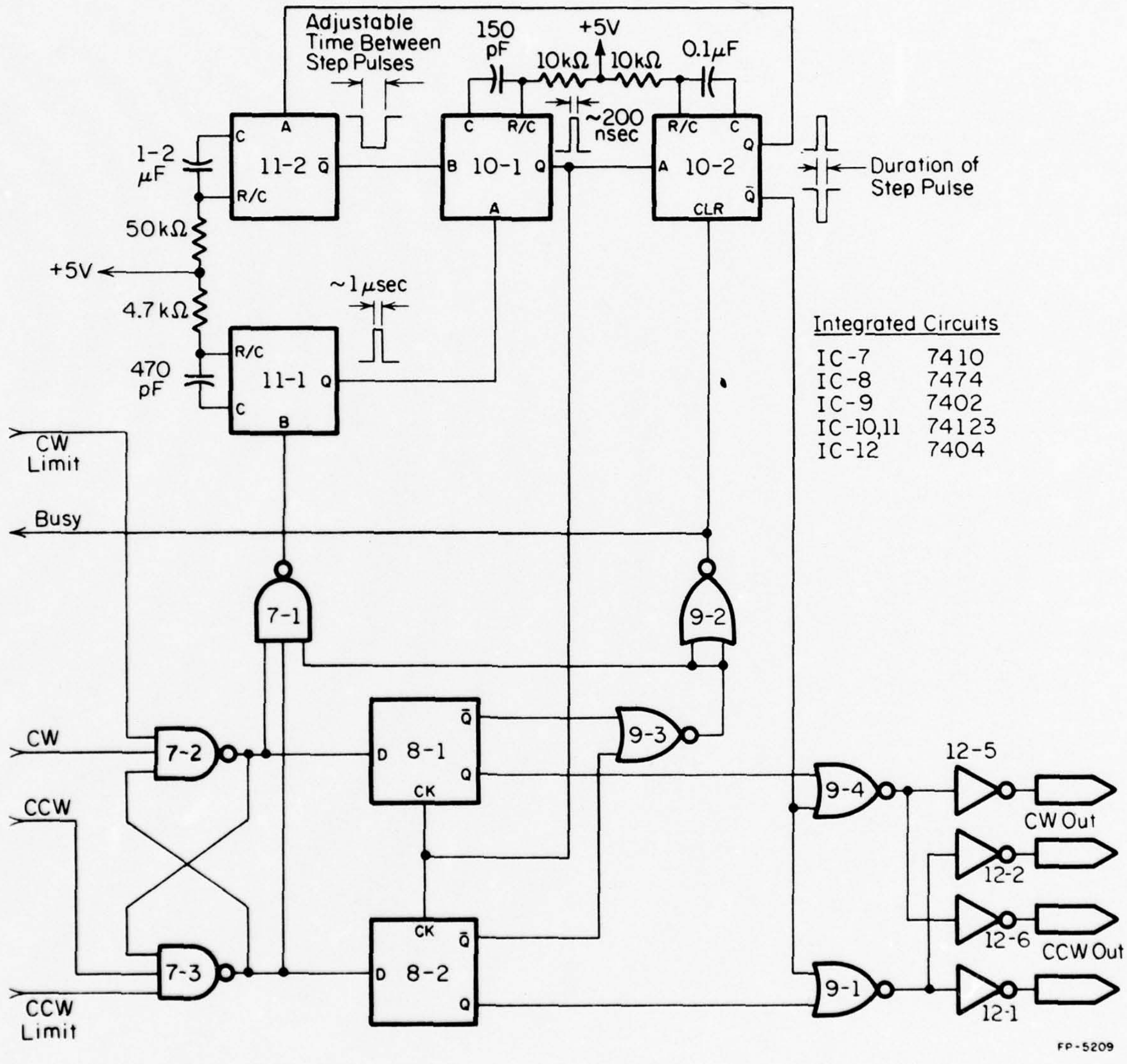


Fig. 14. Step generating circuitry of the motor controller.

clockwise. Each pulse on the output causes the motor driver to step the motor one position in the appropriate direction. An additional pair of inputs correspond to CW and CCW limit switches, although these inputs are not used on the lens controller. When the mirror moves so far as to trip one of these limit switches, the output pulses which have been driving the mirror in that direction are automatically stopped.

These very basic features of the motor controller are embodied in the circuitry shown in Fig. 14. The CW and CCW direction inputs (which connect to Fig. 13) are normally low logic levels; when one of these lines goes high, a sequence of pulses at the corresponding output is produced. If the other input should also go high, it is prevented from having any effect by the pair of cross coupled NAND gates 7-2 and 7-3. These same two NAND gates are used to stop the pulses when a limit switch is activated. The limit switch inputs are normally high, so when one of them goes low, the direction input which goes through the same NAND gate is inhibited.

The controller is fairly immune to noise on the input lines by virtue of the latches 8-1 and 8-2 and the monostable multivibrator 11-1. The latter is triggered when either direction input goes high for the first time after a relatively long pause, and on the falling edge of the pulse produced by monostable 11-1, the the complements of the direction inputs are latched. If the signal which caused the triggering was only a spurious noise pulse, then it will have likely gone away by the time the signal is latched (about a microsecond later), and a spurious step to the motor driver will not occur. Furthermore, the latches are only reloaded just before each new step in a sequence of pulses is to be generated. Hence, any noise occurring on the input lines during the meantime will have no effect.

It is the signal that is latched just before a step pulse is to be generated that determines which output will produce the pulse, if either is at all. If one of the direction inputs was high at the time of the latching, then the corresponding outputs are enabled via the NOR gates 9-1 and 9-4. If neither direction input was high, then no step is produced. In this event, the output of NOR gate 9-3 goes high thus (1) clearing the step-producing monostable 10-2 before it is triggered by the output of monostable 10-1, (2) re-enabling monostable 11-1 to be triggered by an initial input signal, and (3) clearing the output line labelled BUSY. The BUSY line only goes high when step signals are being generated. Also note that the step signal outputs are duplicated. One set goes to the motor driver, while the other set goes to the position register to increment or decrement the position counter.

We now turn to the other half of the motor controller (Fig. 13). Working backwards from the lines connecting to the step generation circuit just described, we find IC-6 which selects between two sets of inputs. The lower set of inputs (B) are from the manual controller, and the upper set (A) are for automatic control. Since this selector is controlled by the AUTO/MANUAL line from the manual control panel, all automatic control is inhibited whenever the range finder is put in manual mode.

Next we find that the inputs corresponding to automatic control come from the output of yet another two-way selector, IC-5. This time, the signal which controls the selector is the INITIALIZE input. This input causes the motor to seek its home position which is sensed by an optical switch on the scanning head. Consequently, a special set of direction commands need to be generated during the initialization process, and the purpose of IC-5 is to switch from the normal direction inputs over to a circuit which seeks home.

The home-seeking circuit works as follows. The cross coupled NOR gates 4-2 and 4-3 initially drive the CCW direction line. If at any time the HOME INDICATOR input goes low, then both NOR gates are turned off thus stopping the CCW drive signal. However, if the home position was not found, then the CCW limit switch will be activated, and this causes the state of the two NOR gates to change so that the motor starts moving in a CW direction. As before, as soon as the home position is reached, the motor will stop. If the home position is not found, then the motor will stop when it reaches the CW limit switch and remain there.

As can be seen, the status of all the switches are made available as outputs on the controller. In fact, very nearly all of the lines terminating at the top of Fig. 13 can be read or written by the PDP-11 via the control and status register (CSR) of the range finder. Whenever the PDP-11 loads the CSR with new data, a pulse on the the WRITE CSR line is generated causing the INITIALIZE and GO bits to be latched into IC-3. These latches are necessary to keep the range finder from moving around randomly when the power to the backplane is turned on; the bits in the CSR would initially be random, but the latches act as a buffer and are cleared by the action of gate 2-4. These latches are also cleared whenever the PDP-11 issues a UNIBUS reset.

We can now consider some of the other blocks which are connected to the motor controllers. The motor drivers and the scanning head need hardly be mentioned. The motor drivers were purchased along with the motors, and all they do is take the pulses coming in on CW and CCW inputs and energize the appropriate windings in the stepper motors. The scanning head merely contains a collection of switches and optical encoders whose effects have been discussed above.

Returning to the backplane, we have the position registers. These are closesly related to the motor controllers in that they close an open loop inherent in the controllers. A block diagram of a position register is given in Fig. 15. Note that there are actually two registers in the circuit, a write-register and a read-register which can be written and read, respectively, by the PDP-11. The read-register is a binary counter where COUNT UP and COUNT DOWN inputs are connected to (duplicates of) the motor driver outputs on the motor controller. Hence, the read-register is incremented or decremented as the motor is stepped one position CW or CCW respectively. The PDP-11 can load the position it would like the motor to go to into the write-register. The contents of the read and write-registers are compared, and the result is made available on two output lines (a third output is not used). These outputs are wired to the direction inputs on the motor

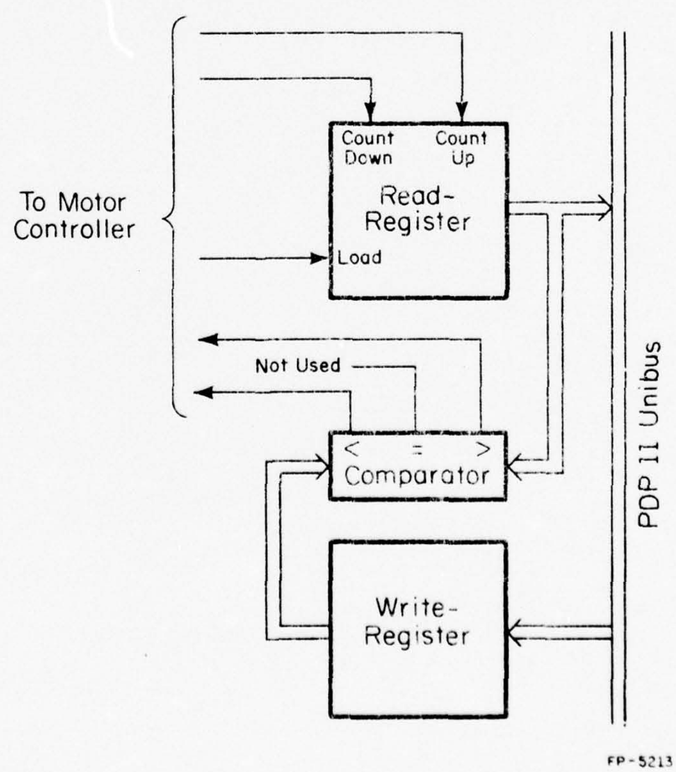


Fig. 15. Block diagram of a position register.

controller so that when the contents of the two registers are unequal, the motor is driven in such a direction as to lessen the difference. When the difference is reduced to zero, the motor stops. Finally, the contents of the read-register are initialized by applying a LOAD signal. This signal is wired to coincide with the INITIALIZE signal applied to the motor controller, and the effect is to load the contents of the write-register into the read-register while inhibiting counting. Hence, while the motor is seeking its home position, the PDP-11 can load the position register with the value it would like the home position to correspond to.

The control and status circuitry consists mainly of a 16-bit register which interfaces to the PDP-11. The assignments of the various bits in the CSR are given in Table 1; most are self explanatory. The numbering of the bits follows the DEC convention [Digital Equipment Corporation, 1973]. There is a small amount of logic circuitry used in conjunction with the CSR. Bit 15 is the logical OR of bits 13 and 14, i.e., whenever a limit switch is activated, the error bit is set. Since it is a standard DEC procedure to use bit 7 for the done bit and since there are both a mirror and a lens which produce independent done bits, a means for selecting between the two was needed. Bits 4 and 5 were used for this purpose. When only bit 4 is set, the mirror done bit is selected, and when only bit 5 is set, the lens done bit is selected. When both bits are set, then the logical AND of the two done bits is used.

The done bit is also used to request an interrupt on the PDP-11. This is accomplished by means of an interrupt card which is also included within the control and status block of Fig. 12. The interrupt card requires only two inputs, an interrupt request and an interrupt enable. An interrupt is

Write Only Bits

Bit 0	Go
Bit 1	Initialize mirror
Bit 2	Initialize lens
Bit 3	Reserved for future implementation of a shutter at the aperture of the laser
Bits 4 & 5	Used to select which done bit is displayed (see text)
Bit 6	Interrupt enable

Read Only Bits

Bit 7	Done bit
Bit 8	Reserved for future implementation of a shutter at the aperture of the laser
Bit 9	Not used
Bit 10	Manual indicator
Bit 11	Home indicator for lens
Bit 12	Home indicator for mirror
Bit 13	Status of CCW limit switch on mirror
Bit 14	Status of CW limit switch on mirror
Bit 15	Error

Table 1. The bits of the control and status register.

produced when the former makes a transition from low to high while the latter is set high. Clearly, the done bit is connected to the interrupt request input, and the interrupt enable input is taken from the same signal on the CSR. It should be noted that the done bit goes high whenever the range finder stops after having been set in motion. Hence, an interrupt can be generated after initializing the range finder as well as after completing normal commands to move about.

Finally, the manual controller deserves a brief mention. Its basic function is to allow manual positioning of the projected laser stripe. For convenience, this is implemented with a joystick where the left-right axis controls the scanning angle, and the up-down axis controls the orientation of the stripe. The manual controller's outputs which go to the motor controllers provide a variable rate sequence of pulses, the rate being controlled by the joystick. So long as each pulse is narrower than the stepping rates actually applied to the motor drivers, the motor controllers can be operated in the mode where one pulse in produces one motor step on the output. There is also a switch for manually interrupting the computer. This makes it possible for a program to request a human operator to position the stripe and to allow the operator to signal completion just as if the motors had been contolled in the automatic mode.

V. CONCLUSION

Although the range finder electronics described above seems to have no flaws, there are several aspects of the scanning head that are worthy of improvement. To anyone witnessing the range finder in operation, the most obvious of these is the noise made by the gear reduction assemblies when being driven by the stepper motors. Since the mirror has a finite range of motion, it was possible to reduce the noise in the mirror assembly somewhat by taking up the backlash in the gears with a spring. However, the same could not be done for the lens assembly because it can rotate all the way around. It has been noticed that frictional damping applied to the shafts of either motor tends to reduce the noise somewhat, but since it is not critical for reliable operation of the range finder, no permanent damping has been installed.

The second problem involves the response of the stepper motors. In order for the position registers to maintain an accurate record of the position of the mirror and lens, the motors must respond to every step command they receive. If the motors are driven too fast, they will lose their position. It is desirable to drive the mirror motor nearly as fast as possible since it takes over 1000 steps to get from one end of its range to the other (although the range within the camera's field of view is normally much less). By trial and error, the maximum rate was found to be about 60 steps per second. The lens, on the other hand, need not be driven so fast since it rotates in such large angular increments. A safe and convenient speed for the lens motor appears to be about 15 steps per second.

The noise and response of the scanning head motors could probably be improved by using small D.C. torque motors instead of stepper motors. However, in order to move the motors to specific positions, additional wires carrying positional feedback would be required, and in order to obtain sufficient accuracy, digital quadrature encoders would have to be used on the shaft of each motor. For the improved performance, this added complexity might be worthwhile, but the stepper motors are certainly adequate when slow speeds and noise can be tolerated.

Finally, there are several problems regarding the quality of the laser stripe produced by the cylindrical lens. The least serious of these is the way the intensity of the light varies along the length of the stripe; it is much brighter near the center than at the ends. There are three or four factors which contribute to this effect, but since the distances and reflectivities of various objects illuminated by the range finder will be subject to wide variations as well, the software for finding the stripe will have to be insensitive to variations in intensity anyway.

A slightly more serious problem is that the range finder does not currently produce a stripe long enough to span from the top to the bottom of the widest angle image produced by the camera. (The camera's maximum vertical field of view is about 32 degrees while the stripe only subtends an angle of about 18 degrees.) Since the laser beam is slightly divergent, the stripe could be lengthened by increasing the length of the optical path from the laser to the scanning head; however, this might cause vibration of the laser beam relative to the scanning head to become a problem. A collimator which increases the beam diameter would not have the problem of vibration, but it would make the stripe wider. Hence, for the time being, a short stripe will

have to suffice.

The most serious problem with the cylindrical lens is that when it is aligned as it ought to be, it produces many fringes parallel to the main stripe. It is believed that these fringes are caused by internal reflections inside the lens interfering with the original light rays. If the lens is tilted so that its lengthwise axis is about five degrees off from being perpendicular to the incident laser beam, then the fringes disappear. When the lens is tilted in this manner, it can be shown that the stripe will be slightly bent into a shape resembling a hyperbola; although, in practice, this bend is not visually apparent. Hence, it is hoped that the bend which is theoretically there will not be more significant than the other sources of error, such as spatial quantization error in the digitized image and uncertainty in the positions of the mirror and lens. In any event, the bend in the stripe will only affect the end portions of the stripe.

APPENDIX A

DRAWINGS OF THE SCANNING HEAD

In Figs. 16-21, detailed views of the scanning head and its components are given. In order to keep the drawings simple, most of the dimensions have been omitted. However, the figures are drawn to scale, so approximate dimensions can be obtained by direct measurement. Note that in the isometric drawings, the dimensions are measured along the projected orthogonal axes (spaced at 120 degree intervals) which therefore causes the objects thus rendered to appear larger than their actual sizes.

FP-5200

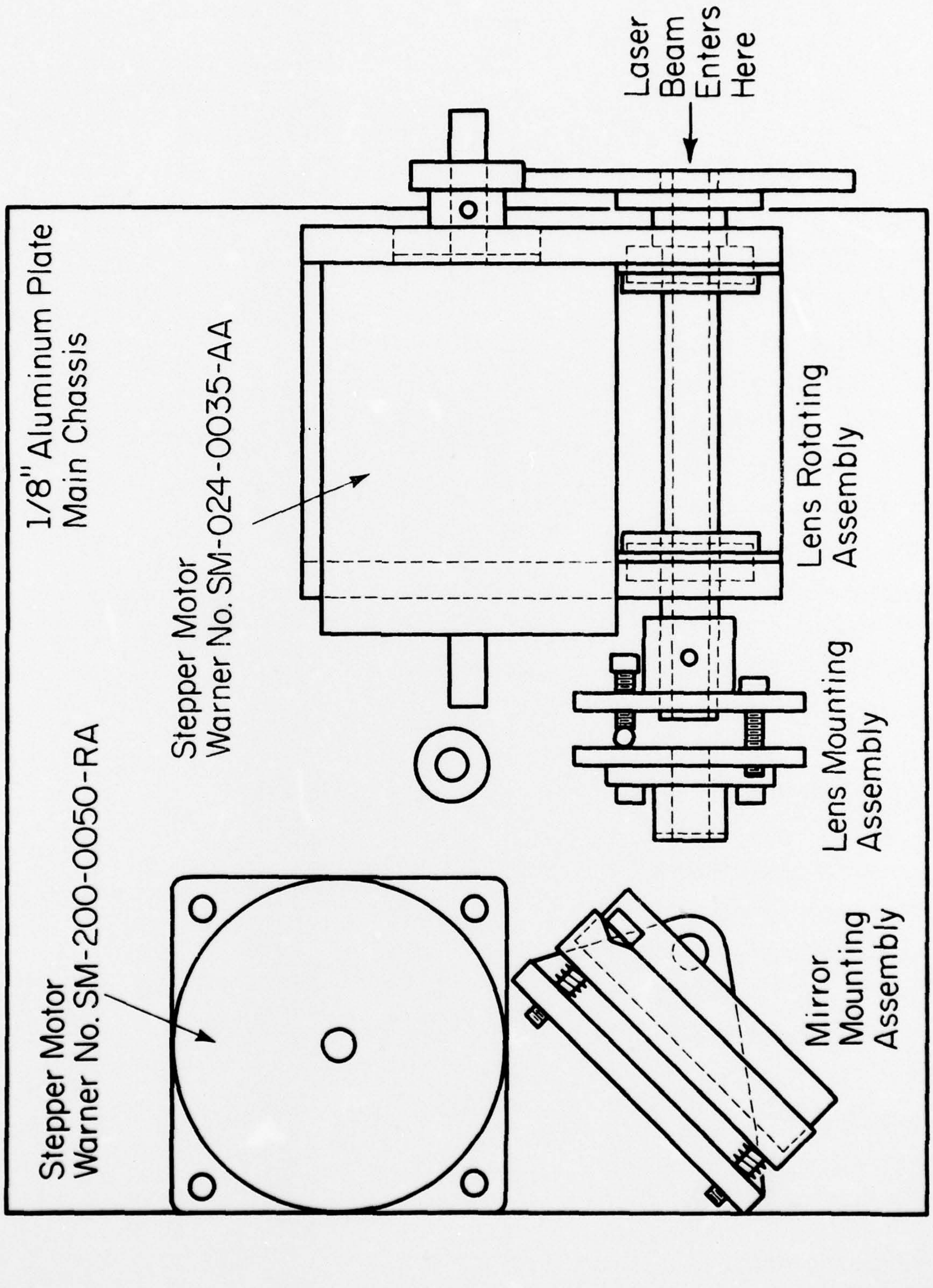


Fig. 16. Layout of the scanning head.

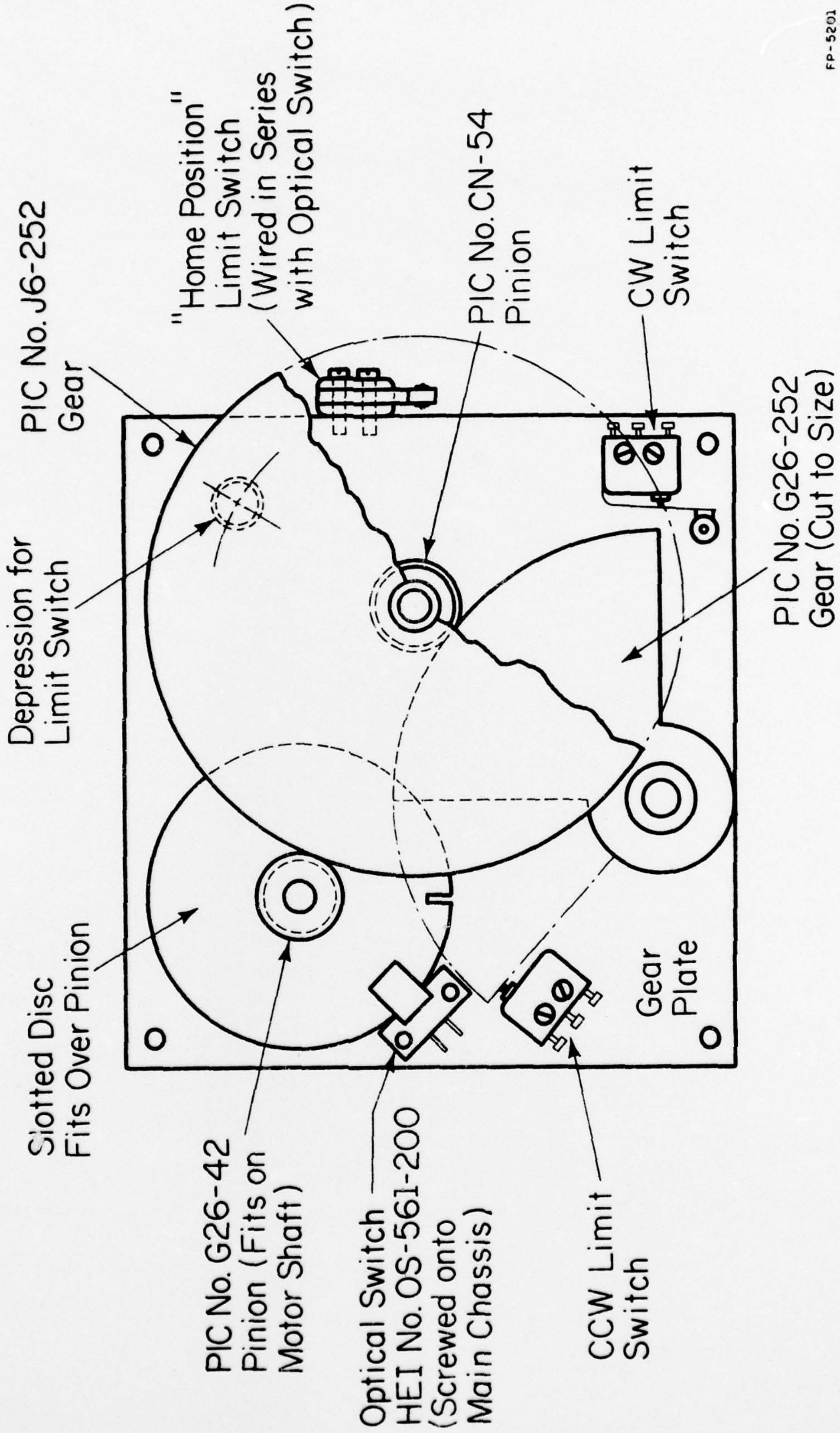


Fig. 17. Reduction gear assembly underneath the main chassis.

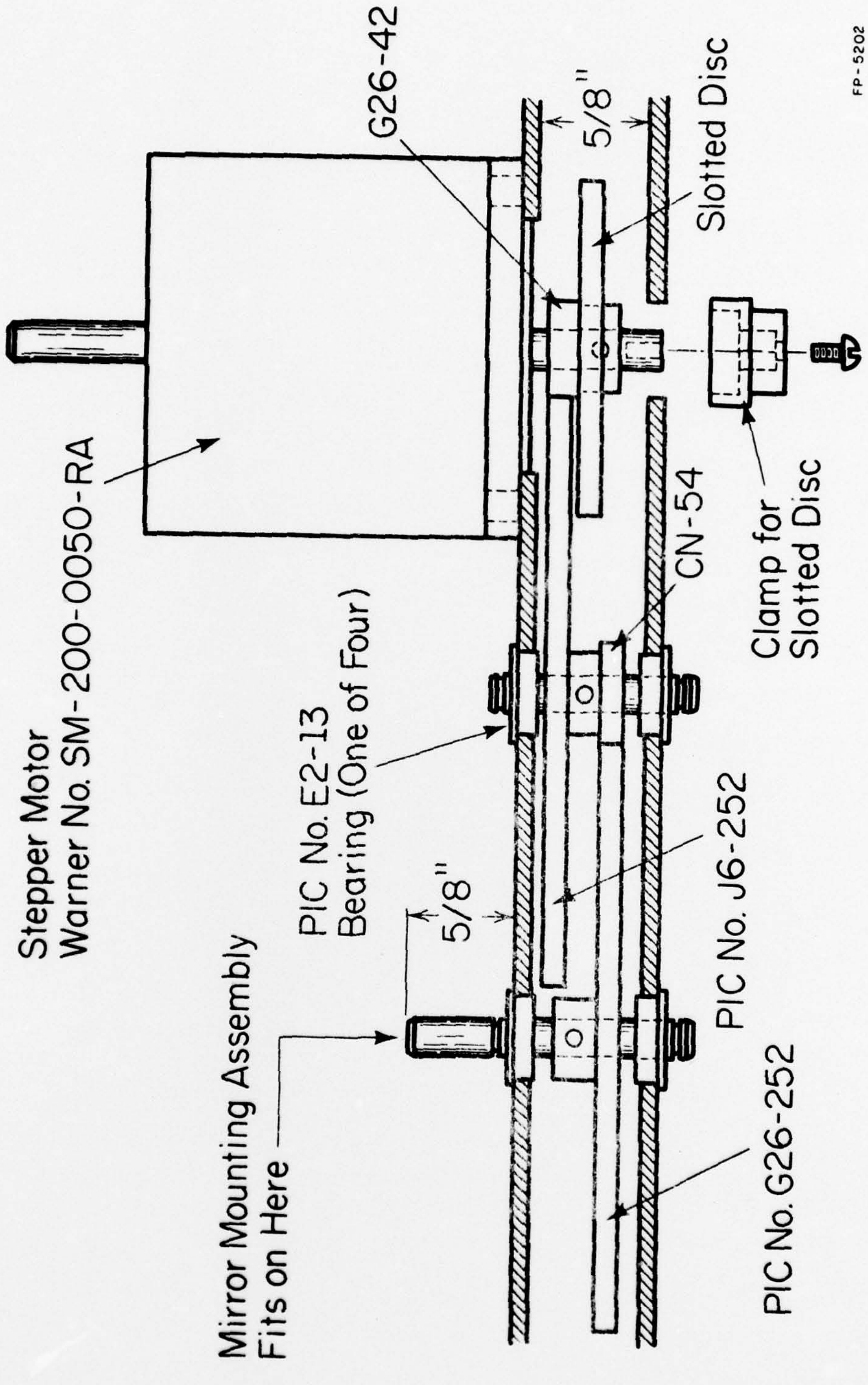


Fig. 18. Detail of the reduction gear assembly.

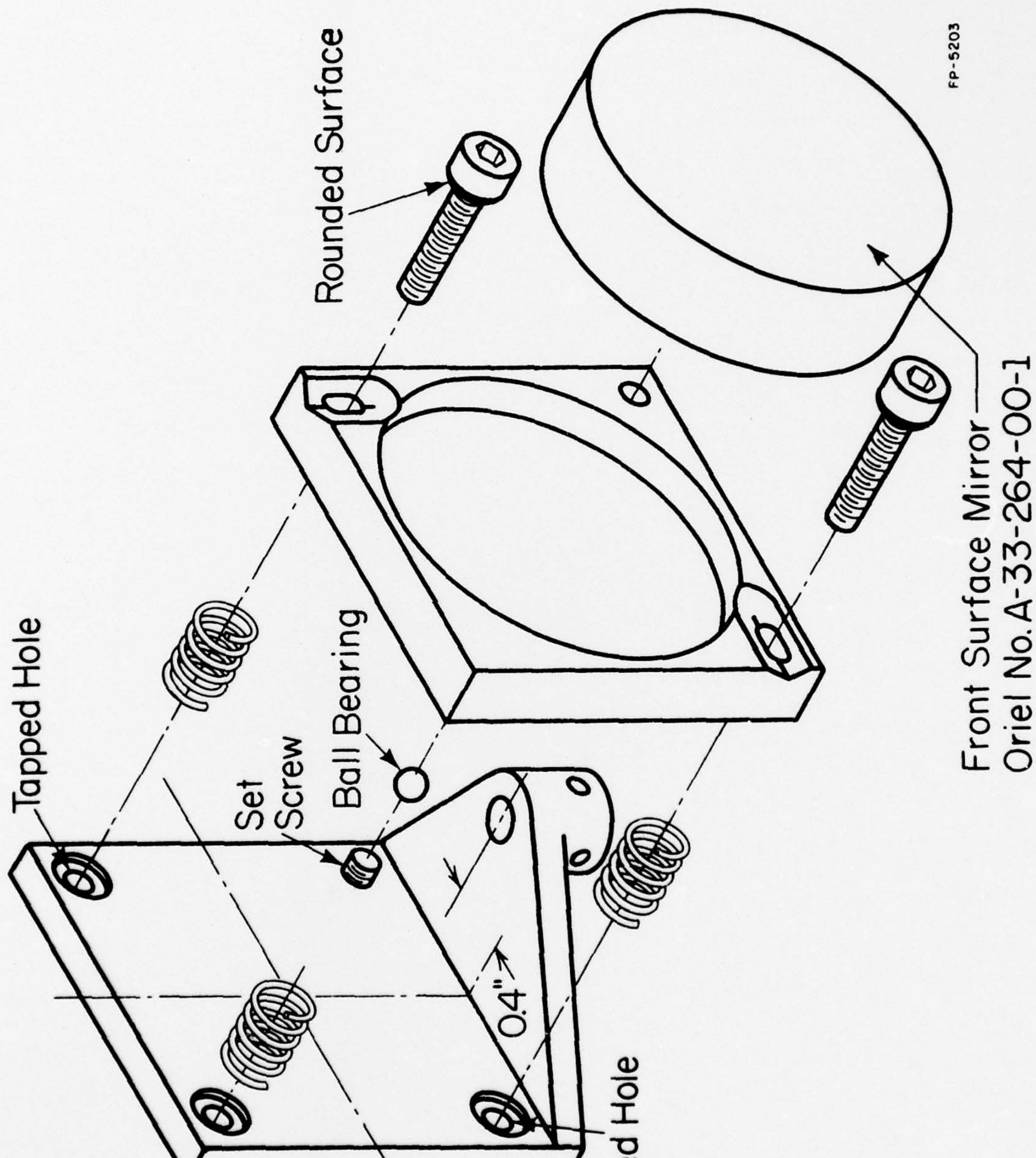


Fig. 19. The mirror mounting assembly.

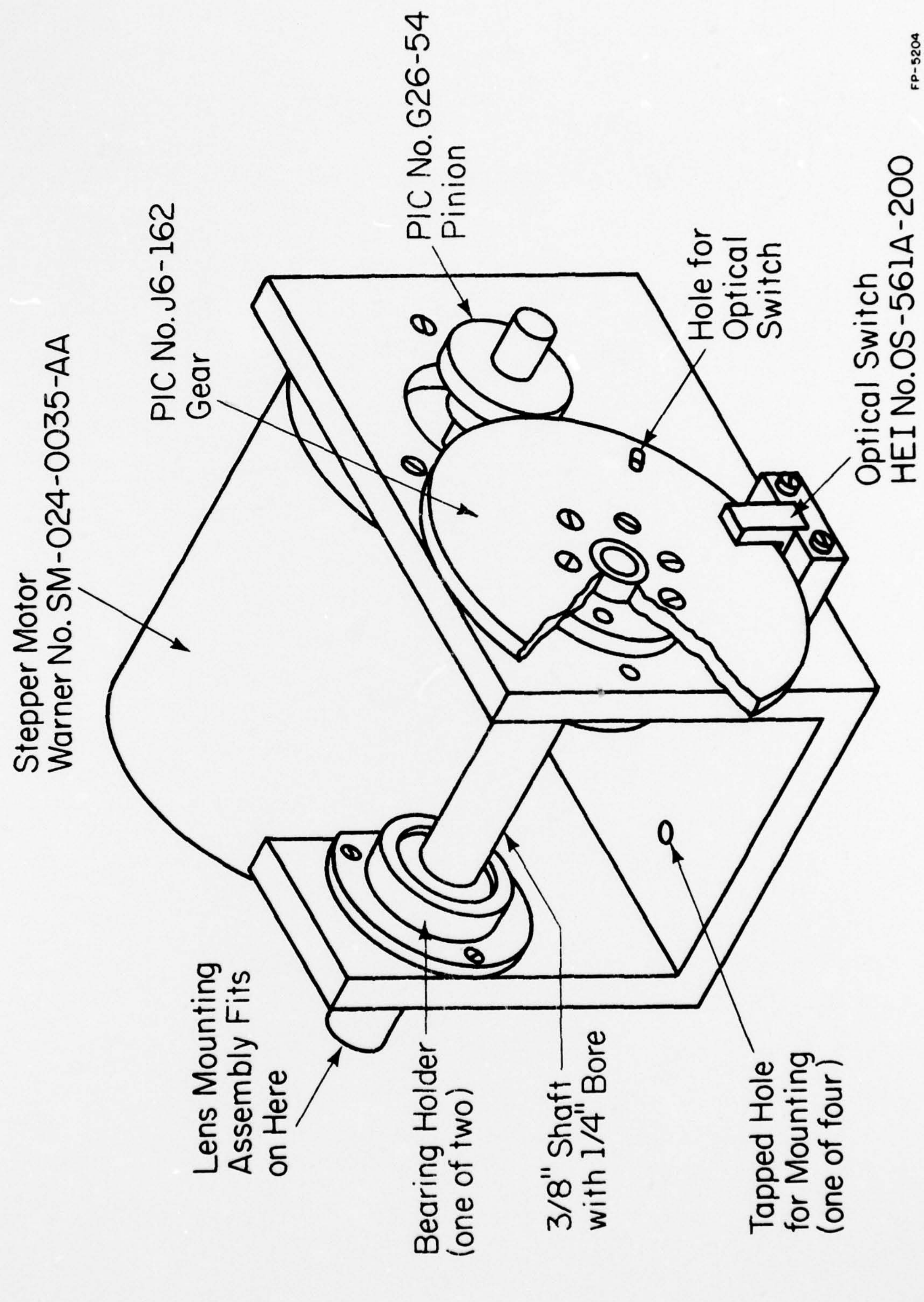


Fig. 20. The lens rotating assembly.

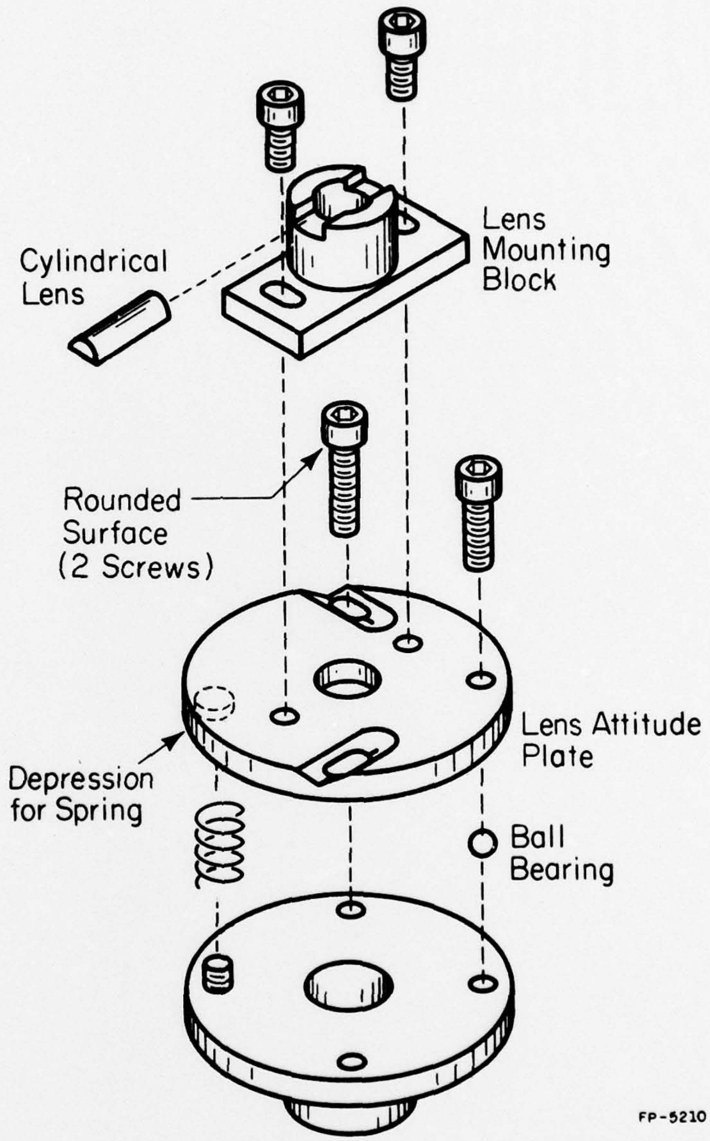


Fig. 21. The lens mounting assembly.

APPENDIX B

ALIGNMENT OF THE SCANNING HEAD

Altogether, there are seven components requiring alignment. These include two small mirrors which deliver the laser beam to the scanning head, the lens rotating assembly, the cylindrical lens mounting assembly, the scanning mirror, and the two optical switches which sense the home positions of the rotating lens and the scanning mirror. Since some of these components must be aligned before others, and since such alignment is fairly difficult without the aid of some very special alignment tools, a detailed discussion of the proper procedure to follow is given below.

First of all, the home sensing apparatus on the mirror assembly requires a preliminary alignment that can only be done with the scanning head removed from the pan-tilt platform. Since the motor turns around six times as the mirror moves from stop to stop, an additional limit switch on the second gear is wired in series with the optical sensor on the motor. The recession in the face of this second gear must be aligned with the switch when the mirror is turned approximately 45 degrees from the axis of the incident laser beam. To make this alignment, first position the mirror mounting assembly on the shaft it rotates about so that the total scanning range is equally distributed about the 45 degree position. Then, turn the mirror fully clockwise until the gear connected to the mirror becomes disengaged. The rest of the gears and the motor can now be turned freely without moving the mirror. After re-engaging the gears, see if the recession in the second gear is properly aligned, and if not, try again.

The next item that should be adjusted is the lens rotating assembly. The axis of the hollow shaft must be aimed so that it intersects the axis that the scanning mirror rotates about. This adjustment is best accomplished with two special instruments which extend these axes closer to the point of their intersection. Both of these instruments are simply rods with pointed ends, one six to eight inches long which fits snugly inside the bore of the hollow shaft, and the other about an inch and a half in length with a hole bored in the center of the non-pointed end so that it fits snugly over the shaft that the scanning mirror attaches to. Of course, the mirror and lens mountings need to be removed before these rods can be inserted in their respective places. When this is done, slide the lens rotating assembly about until the points of the two pointed rods can be made to coincide.

The third item to be aligned is the first delivery mirror that the laser beam encounters. It is necessary that the laser beam intersect the second mirror at precisely the same point as does the axis of the hollow shaft on the lens rotating assembly. Insert the long pointed rod through the hollow shaft so that the point almost touches the second mirror. Then adjust the two alignment screws on the first mirror to make the laser beam fall squarely on the point of the rod. It should be noted that when adjusting the mirror (and all the other mirrors on the range finder as well), one screw moves the laser beam up and down while the other screw moves the beam right and left.

Alignment of the second delivery mirror is next. The laser beam must coincide with the axis of the hollow shaft on the lens rotating assembly. On the end of the shaft where the lens mounting assembly goes, put a piece of translucent tape with a quarter inch circle and crosshairs drawn on it. The circle should correspond to the bore of the shaft, but to verify that the

crosshairs are properly centered, spin the shaft to see if the center of the crosshairs remains stationary. Then adjust the second mirror until the laser beam is centered in the crosshairs.

Now that the incident laser beam is correctly positioned, the lens rotating assembly requires several more adjustments. Turn the gear on the shaft of the stepper motor so that when the motor is energized, the hole in the larger gear lines up with the optical sensor. Next, insert the lens mounting assembly on the hollow shaft so that the projected stripe is approximately vertical. The adjustment which makes it exactly vertical is to be made later. Now, slide the lens mounting block up or down until the stripe is centered about the axis of the laser beam. Finally, adjust the lens attitude plate so that the beam reflected by the flat side of the lens is parallel to the incident beam, and then lower one end of the lens until the fringes on either side of the stripe go away.

Next, the scanning mirror needs to be adjusted to line the surface of the mirror up with the axis of the mounting hole on the mirror mounting assembly. Insert this assembly onto its shaft. One half of the end of the shaft should be visible in the mirror and should appear to be part of the actual shaft, as if the mirror were not really there. While looking down on the end of the shaft, adjust the screw holding the ball bearing until the shaft looks perfectly round. Then, while viewing the end of the shaft from a lower angle, adjust the screw at the top of the mirror assembly until the top of the shaft looks perfectly flat. Note that this alignment requires sharp eyes.

Finally, the home position of the mirror and lens can be set. After advancing the lens motor 18 steps beyond its home position (rotating the lens by 90 degrees), turn the lens mounting assembly on the hollow shaft until the stripe is exactly parallel with the raster lines in the television image. Also, if the stripe is not approximately half way up in the image, then it should be made so by adjusting the tilt of the camera on the pan-tilt platform.

To complete the adjustment of the home position on the mirror, turn the stripe so that it is vertical and drive the scanning motor until the light is being projected parallel to the optical axis of the camera. The limit switch in series with the optical sensor should now be closed. Then turn the disc which blocks the optical sensor so that the slit in the disc causes the output of the sensor to go low.

One final note: these last two steps may not align the range finder with the true optical axis of the camera, but to a very close approximation, an axis can be defined slightly off center in the image from which the angles to other points in the image are measured.

REFERENCES

Agin, Gerald J. and Binford, Thomas O. "Computer Description of Curved Objects." Third International Joint Conference on Artificial Intelligence. Stanford, Calif.: Stanford, University, 1973.
Reprinted in IEEE Transactions on Computers C-25 (April, 1976): 439-49.

Digital Equipment Corp. PDP-11 Peripherals Handbook. Maynard, Mass.: Digital Equipment Corp., 1973.

Geschke, Clifford Calvin. "A Step Motor Controller for a Pan/Tilt Head." Master's Thesis, University of Illinois at Urbana-Champaign, 1975.

Williamson, Donald Alan. "A Digital Positional Controller for a Television Zoom Lens." Master's Thesis, University of Illinois at Urbana-Champaign, 1975.